EVALUATION OF CO-INJECTION MOLDING: AN ALTERNATIVE TO RECYCLING SCRAP PAINTED BUMPERS

by

Emily Cortright

Senior Honors Thesis

The Ohio State University

Submitted to the Department of Industrial, Welding, and Systems Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Industrial and Systems Engineering

June 2007

Approved by:

____
Thesis Project Director

____
Departmental Honors Director (or College Advisor, etc.)

____
Coordinator, Honors Program

Table of Contents

List of Figures

List of Tables

Chapter I. Introduction

Injection molding (IM) is one of the most prominent processes for mass-producing plastic parts, as it allows for very complex geometries and small dimensions. As technology advances, however, improvements to current injection molding processes allow for even increased usefulness, applicability, and profitability for manufacturers across the world. One process capable of these improvements is co-injection molding.

There are two types of co-injection molding: multi-component (or two-color) and "sandwich molding." Multi-component molding involves the sequential injection of two polymers into a two-position mold [2]. This technology is used in products such as computer keys and multi-colored automotive tail-lights [1]. Sandwich molding is characterized by products that are comprised of a core material surrounded by an outer, skin material (see Figure 1b). This "sandwiched" topology is created by injecting two different plastics either simultaneously or in rapid sequence through the same gate of a specialized injection molding machine. This co-injection molding machine has two separate, individually controlled injection units with one common injection nozzle and a switching head (see Figure 1a). The remainder of this report will focus on sandwich molding, which will hereafter be referred to generally as co-injection molding (CIM).

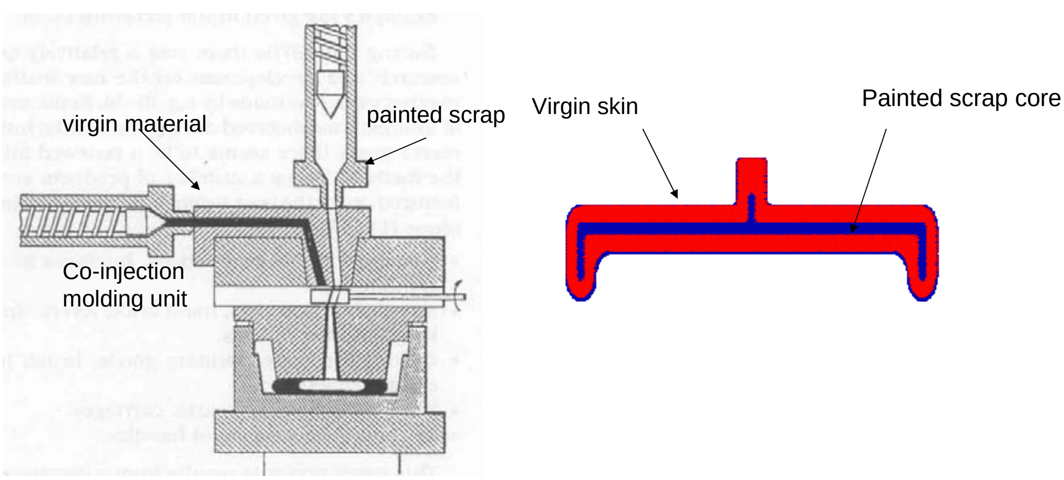

Figure 1: a) Sandwich molding machine with two injection units, one common nozzle, and a switching head [4]; b) Finished product cross-section.

Implementing CIM into manufacturing processes can benefit both a company and the Earth. Honda recently began studying the use of recycled material for their bumpers, which are made out of thermoplastic polyolefin (TPO). Any bumpers that are declared “scrap” before being painted can simply be ground up and re-used in the injection molding process. Comparison of physical properties (tensile, flexural, and impact) measured in our lab [5] against Honda’s specifications indicate that they can use up to 80% of recycled TPO without detrimental effect on the bumper’s properties. This limit is much higher than their current scrap levels. The dilemma occurs, however, after the bumpers have been painted. At this point, when the product does not meet quality standards, there are no present recycling capabilities. The painted scrap, if molded and mixed with the virgin material, even in small amounts will not give an acceptable surface quality. Measurements taken in our labs indicate that physical properties of such mixtures meet Honda specifications at levels of scrap painted bumper below 10% by weight. Typical scrap levels of painted bumpers are under 10%. At the present time, the scrap painted bumpers are discarded as waste. It is anticipated that co-injection molding will allow the painted bumpers to be re-grinded and used as the inner core of a new bumper (Figure 1b above). This research will identify the conditions needed to avoid core surfacing in the bumper. The goal for Honda will be to maximize the amount of recycled material used while meeting the current specifications. This will potentially save Honda over $2 million per year by reducing material costs and waste.

In order to determine the most efficient process parameters and the maximum amount of recycled painted scrap material, Design of Experiments (DOE), as well as multi-variable optimization such as Data Envelopment Analysis (DEA), will be used. The statistics software package MINITAB will analyze the data and form a final fit model for each performance measure, showing how each input variable affects the performance measure.

Chapter II. Injection Molding

Injection molding (IM) is one of the leading processes for mass-producing plastic products. Selecting the proper settings for an IM greatly affects the part's mechanical properties, such as tensile strength (TS), impact resistance, and flexural strength (FS), as well as surface quality. Factors such as mold temperature, melt temperature, flow rate, packing pressure, and packing time are all critical to achieving an acceptable product. Adjusting one factor will likely affect another; for instance, increasing the temperatures will decrease the viscosity of material and it will flow easier. This will decrease the injection time and overall cycle time, but will require more energy, leading to higher operating costs. Lowering the temperature will cause the material to have a higher viscosity, increasing the cycle time and requiring more packing and molding pressure. Machines are limited to certain pressures based on the units installed.

Typical defects in injection molding include burnt parts, warpage, and surface imperfections. Burnt parts may be the result of the melt temperature being too high or the cycle time being too long, allowing the resin to overheat. Warpage is caused by uneven surface temperature of the mold or non-uniform wall thickness of the part. Surface imperfections can be caused by excessive melt temperature which results in resin decomposition and gas bubbles; excess moisture in the resin; or insufficient pressure, which causes incomplete filling of the mold.

Chapter III. Technical Background

3.1 Co-Injection Molding

Co-injection molding was first patented in 1969 as an alternative to the structural foam process, and has been commercially used since 1975. The primary factors in CIM are the viscosity and volume ratios of the two materials. However, mold geometry and processing conditions (injection speed, packing pressure, etc.) also affect the final product. Figure 2 illustrates the effect that viscosity ratio can have on the skin/core distribution. The thickness uniformity, length of core penetration, and physical properties of the final product are all affected by the viscosity ratio of the two materials. From the graph, it is evident that the most uniform thickness distribution can be obtained by injecting a core with a slightly higher viscosity than the skin.

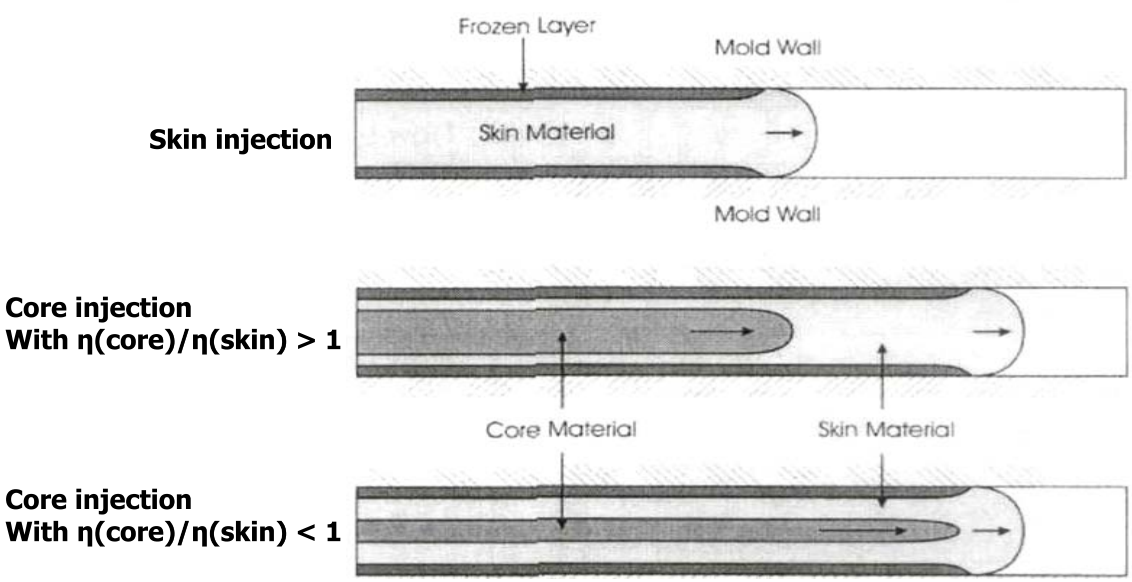

Figure 2: Effects of viscosity ratio on thickness distribution of the core material [3].

One common defect in CIM is the breakthrough phenomena, caused by using an improper volume ratio that gives rise to the core material breaking through the skin material to the surface of the product [6]. Other processing conditions besides the volume ratio, such as injection speed or time, and melt and mold temperatures, can also cause this defect. Figure 3 shows the relationship between flow length of the skin and core materials for a co-injection molding process for a case where the breakthrough phenomenon occurs. The graph is divided into four regions: 1) the skin material is injected, 2) the skin injection stops and core material is injected, 3) the core flow front reaches the skin flow front but does not break through (the two materials advance together), and 4) the core flow front breaks through the skin flow front (the core material will appear at the surface of the product) [7].

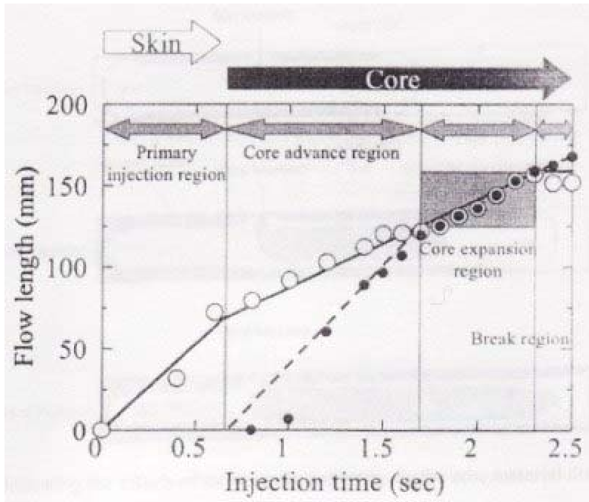

Figure 3: Flow length relationship with injection time for core and skin when breakthrough occurs [7]

The injection gate selection, another factor determining core distribution, is illustrated by Figure 4. When the core is injected, it will not penetrate any part of the mold that has already been completely filled by the skin material. This is because there is no room to displace the skin material. Therefore, the injection gate selection is crucial in co-injection molding in order to achieve a balanced core distribution [8].

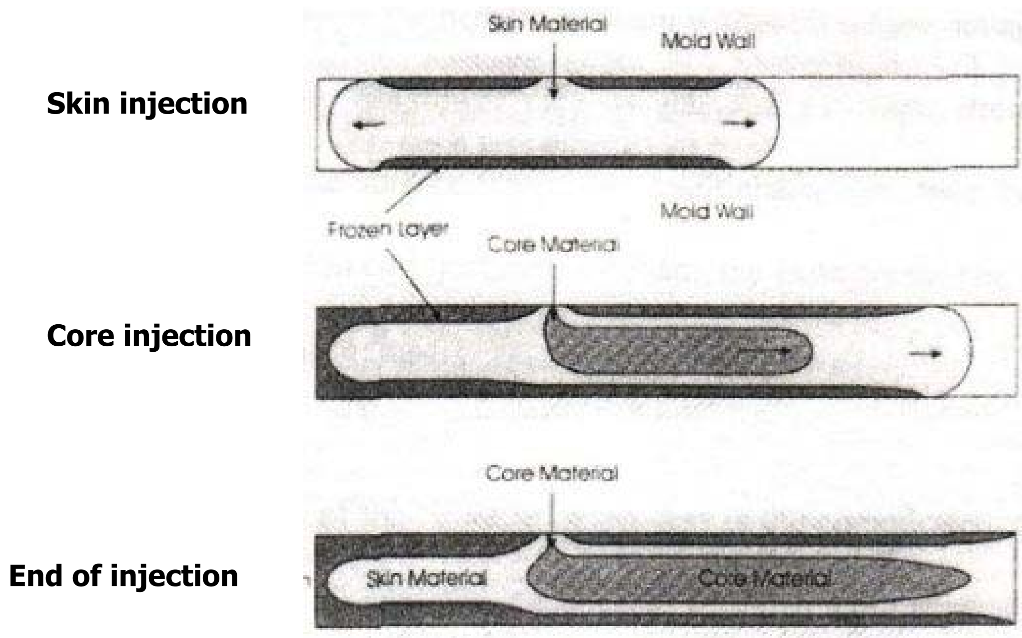

Figure 4: Illustrating the effects of injection gate location on the core material distribution [8]

3.2 Statistical Optimization

Data envelopment analysis (DEA), occasionally called frontier analysis, was first introduced in 1978 and is a performance measurement technique that evaluates the efficiency of a number of inputs. DEA can be a powerful tool when used wisely. For example, it can handle multiple input and output models and doesn't require an assumption of a function form relating inputs to outputs. It also allows inputs and outputs to have varying units [9].

With three or fewer performance measures, the results of testing are graphed and the extreme points form a line called the efficient frontier. The efficient frontier defines the points that cannot be improved without harming another performance measure. The user then determines which point on the efficient frontier best meets their personal requirements. It is when there are greater than three performance measures that DEA software becomes a critical tool, as graphs are no longer feasible. The software used for this research is able to determine the most efficient points considering up to ten performance measures.

Analysis of Variance (ANOVA) is a standard approach for analyzing significance of factors or model terms and is usually followed by multiple t-tests. The statistical package MINITAB was used to run Response Surface Regression, a type of ANOVA, on all the data points. Response Surface Regression is a combination of polynomial regression and fractional factorial regression designs, containing variables to the degree of two and the 2-way interaction effects of the variables.

Chapter IV. ASTM Analysis

The ASTM D 638 dogbone was used for the *MoldFlow* analysis using the software and simplified fluid mechanics models for two-phase flow. The dimensions and picture can be seen below in Figure 5. This test part was selected because of the need to develop a material database and to evaluate the validity of the testing sample. This will help determine the uniformity of the center section. An end injection point was also chosen to help achieve uniform distribution in the center portion of the dogbone.

Dimensions (see drawings)		mm	
W	— Width of narrow section	6	(0.25)
L	— Length of narrow section	33	(1.30)
WO	— Width over-all, min	19	(0.75)
LO	— Length over-all, min	115	(4.5)
D	— Distance between grips	64	(2.5)
R	— Radius of fillet	14	(0.56)
RO	— Outer radius	25	(1.00)

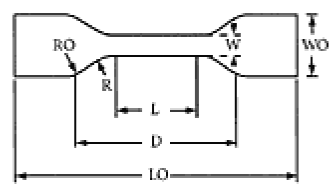

Figure 5: ASTM dogbone dimensions

Four factors were used in the analysis: mold temperature (T_{mold}), melt temperature of skin material (T_A), melting temperature of core material (T_B), and % core injected. All temperatures were measured in degrees Celsius. The levels of T_{mold} were 15°, 20°, and 25°. The levels for both T_A and T_B were 220°, 240°, and 260°. The levels for % core injected were 10%, 20%, and 30%. The core was injected after half of the skin had been injected, during the middle of the run. The format for referencing a run will hereafter be referred to as T_{mold} _T_A _T_B _%core. For example, 15_220_240_15% would signify a run with a 15° mold temperature, a skin temperature of 220°, a core temperature of 240°, with 15% core. A full factorial design was used, and therefore, all combinations of factors and levels were tested.

For every MoldFlow trial, the percent core was taken at each of five designated points (see Figure 6), and were used to determine two of the four performance measures. The performance measures were maximum pressure (MPa); the distance of maximum core from the center (mm); the difference between the maximum and minimum of Point 2, 3, and 4 (% core); and difference between Point 1 and Point 5 (% core). These were chosen to evaluate uniformity throughout the dogbone.

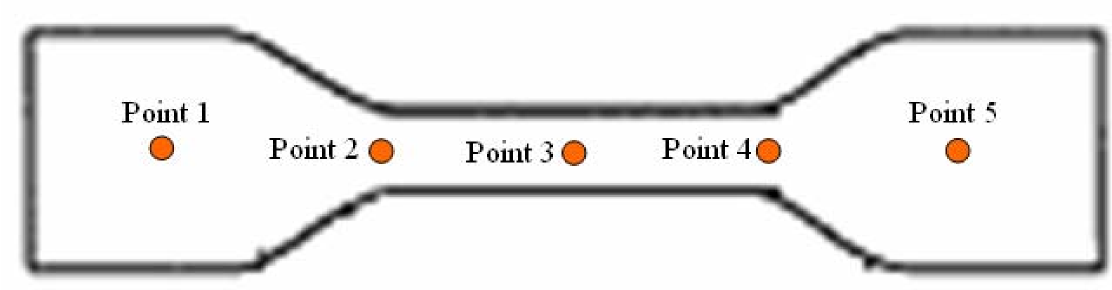

Figure 6: Percent core data points taken for each dogbone trial

Chapter V. Results

The data points for each trial were entered in an Excel spreadsheet. First, the entire set of data points was run through DEA software. This gave seven efficient points, which can be seen in Table 1. Six of the seven points had 10% core, and one had 30% core; there were no 20% core trials. Next, the points were categorized by % core and the DEA analysis was run again using all four performance measures, then only two performance measures (distance of maximum core from the center and difference between the maximum and minimum in the center). These results are also seen in Table 1.

All Data Points	**10% Trials**		**20% Trials**		**30% Trials**	
4 PM's	**2 PM's**	**4 PM's**	**2 PM's**	**4 PM's**	**2 PM's**	**4 PM's**
15_220_240_10	15_260_220	15_220_240	25_260_220	20_220_260	15_220_260	15_220_260
15_260_220_10	15_260_240	15_260_220		25_260_220	20_240_260	20_240_260
15_260_260_10		15_260_240		15_260_260	20_260_260	25_240_260
20_220_260_10		15_260_260				20_260_260
20_260_260_30		20_240_240				25_260_260
25_220_260_10		25_220_260				
25_260_220_10		25_240_240				
		25_260_220				

Table 1: DEA Results

Two specific trials appeared in all three possible circumstances, and are highlighted above: 15_260_220_10% and 20_260_260_30%. These trials were two of the first to be considered for the preliminary bumper runs. The thickness fraction of the core material for these two runs can be seen below in Figure 7. In this and the following similar graphs blue represents 0% core and red represents the maximum amount of core.

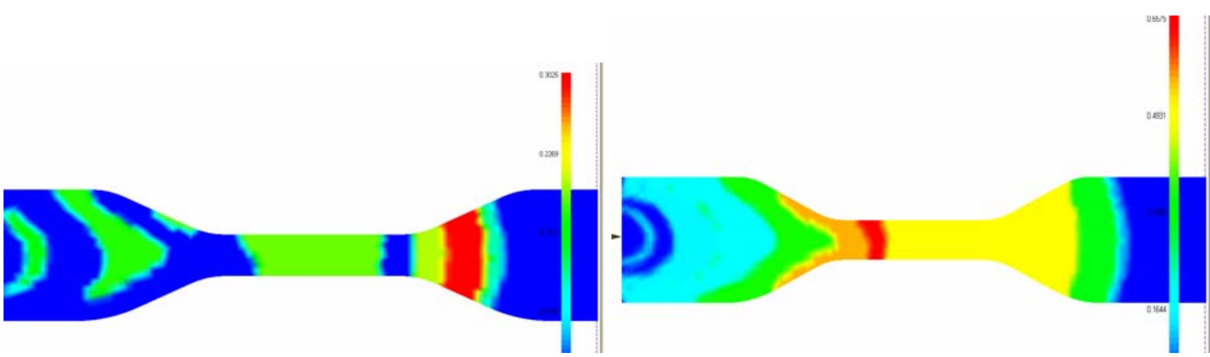

Figure 7: Top two DEA results: a) 15_260_220_10%; b) 20_260_260_30%

Compare the screen shots in Figure 7 to the best visual result showing the most uniform thickness throughout the center of the dogbone shown in Figure 8 below. This is trial 15_220_260_30% and was an optimum trial in both 30% DEA runs but not when all data points were analyzed together.

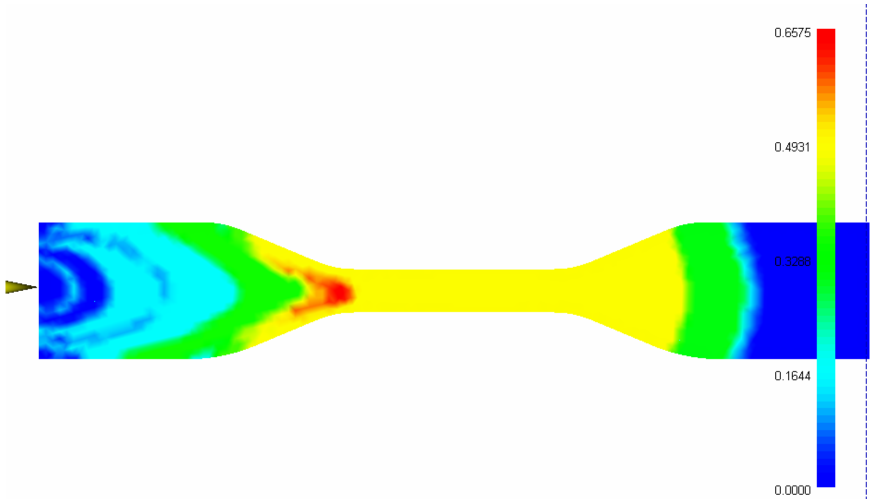

Figure 8: 15_220_260_30%, best visual result of uniform thickness throughout the center of the dogbone

The worst visual cases were 15_220_240_10% and 15_260_260_10%, and can be seen in Figure 9. In Figure 9a, the percent core jumps drastically from about 20% to 30%, where the red and yellowish-green meet in the center of the dogbone. In Figure 9b, there is a section of the center of the dogbone that contains no core material (the small blue portion). Both these circumstances are undesirable when testing for uniformity of distribution. It is interesting to note that one of the best results from the DEA testing, trial 15_260_220_10%, also exhibited a portion of the center where no core material accumulated (Figure 7a). This illustrates a flaw with using five distinct points for data collection analysis, as this method was unable to detect this type of flaw.

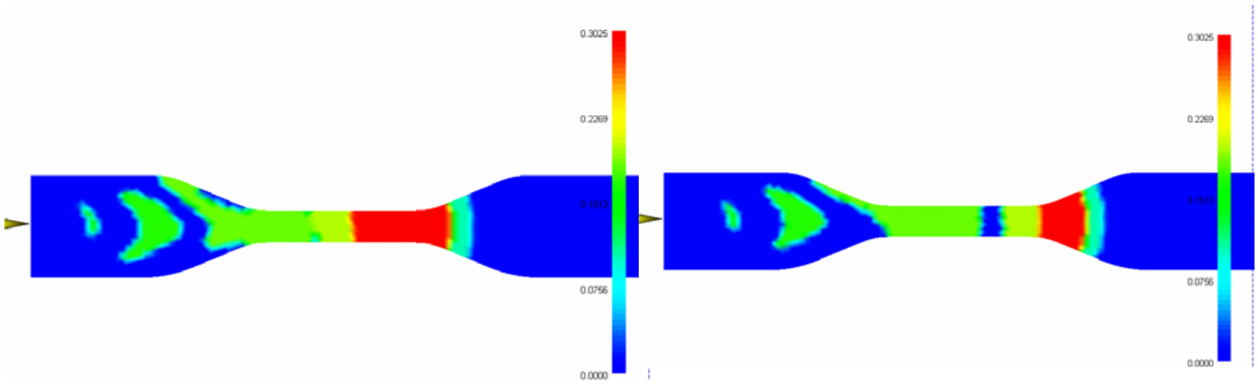

Figure 9: Worst visual trials: a) 15_220_240_10%; b) 15_260_260_10%

The data was entered into MINITAB and analyzed using Response Surface Regression. With full factorial data, the original fit model contained quadratic terms and all combinations of the terms. For clarity, the input variables will be referred to as the following: mold temperature (A), melt temperature of skin material (B), melt temperature of core material (C), and % core injected (D). The template of the fit model is the following:

Performance Measure = $\beta_1 + \beta_2 A + \beta_3 B + \beta_4 C + \beta_5 D + \beta_6 A^2 + \beta_7 B^2 + \beta_8 C^2 + \beta_9 D^2 + \beta_{10} AB + \beta_{11} AC + \beta_{12} AD + \beta_{13} BC + \beta_{14} BD + \beta_{15} CD$

Three iterations were completed for each performance measure, removing the terms with p-values greater than 0.100. The final fit models for each performance measure are seen below in Figure 10.

$$\textbf{Max Pressure} = 17.7477 - 0.0301A - 0.0372B - 0.0043C - 0.0266D + 0.0007BD - 0.0006CD$$

$$\textbf{Distance of maximum core from center} = -108.779 + 2.153A + 0.596B - 0.109C + 3.739D - 0.026D^2 - 0.009AC - 0.026BD - 0.014CD$$

$$\textbf{Difference between Points 2, 3, and 4} = -0.7239 + 0.0011A + 0.0021B - 0.0003C + 0.0830D - 0.0015D^2 - 0.0001BD$$

$$\textbf{Difference between Point 1 and 5} = 2.4963 + 0.0011A - 0.0093B - 0.0119C + 0.0140D - 0.0003D^2 + 0.00004BC - 0.00005BD + 0.00004CD$$

Figure 10: Fit models for each performance measure

The p-value charts for each performance measure after the three iterations are shown below in Figure 11a-d.

Term	P
Constant	0.000
T mold C	0.000
A T melt C	0.000
B T melt C	0.166
% Core	0.588
A T melt C*% Core	0.000
B T melt C*% Core	0.000

Figure 11a: Max Pressure p-values

Term	P
Constant	0.000
T mold C	0.025
A T melt C	0.000
B T melt C	0.222
% Core	0.000
% Core*% Core	0.000
T mold C*B T melt C	0.022
A T melt C*% Core	0.000
B T melt C*% Core	0.000

Figure 11b: Distance of maximum core from center p-values

Term	P
Constant	0.002
T mold C	0.386
A T melt C	0.016
B T melt C	0.270
% Core	0.000
% Core*% Core	0.000
A T melt C*% Core	0.016

Figure 11c: Difference between maximum and minimum in center p-values

Term	P
Constant	0.000
T mold C	0.122
A T melt C	0.000
B T melt C	0.000
% Core	0.061
% Core*% Core	0.000
A T melt C*B T melt C	0.000
A T melt C*% Core	0.023
B T melt C*% Core	0.036

Figure 11d: Difference between Point 1 and Point 5 p-values

Chapter VI. Honda Bumper Preliminary Results

The initial bumper trials used a model with injection points on the top of the bumper, and the core was injected after half the skin was injected. First, selected optimal trials from each percent core group were run, including the two aforementioned trials that were optimal in all three circumstances. Screen shots can be seen below in Figure 12a-c.

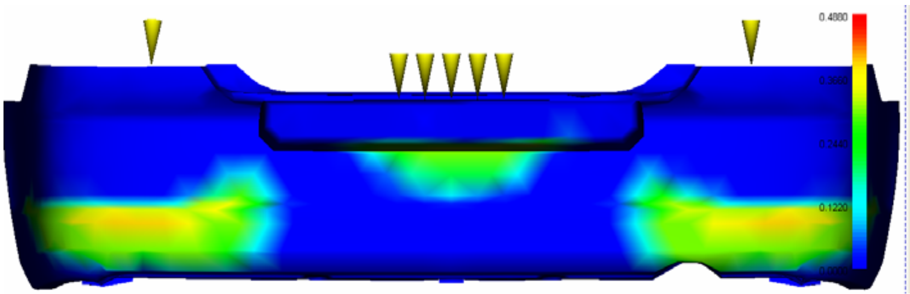

Figure 12a: 15_260_220_10%

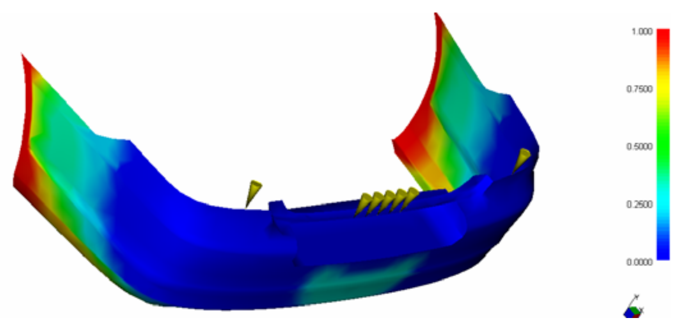

Figure 12b: 20_220_260_20%

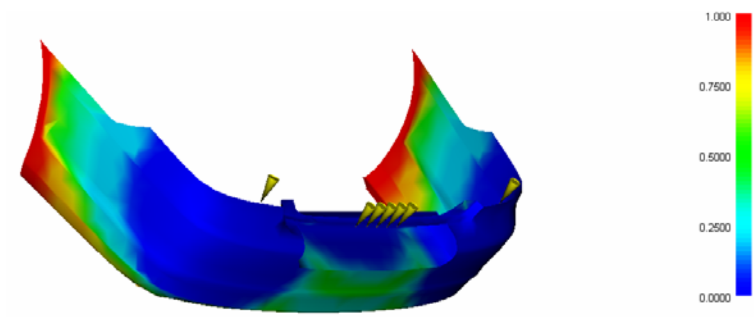

Figure 12c: 20_260_260_30%

Both the 20% and 30% core trials, Figure12b and Figure12c, showed core surfacing at the back edges of the bumper. This can be seen in the thickness fraction plot where the red indicates 100% core. The 10% trial, Figure 12a, showed no core surfacing, only that the core accumulated towards the bottom corners and center of the bumper. The highest core thickness barely reaches 38%. These preliminary runs proved that co-injecting 20% core or higher into the bumper will cause core surfacing and therefore, all 20% and 30% trials will no longer be considered candidates for the optimal solution.

Next, a different approach was taken. Trials were run with the material being injected from the bottom with 5%, 10%, and 15% core. Both 5% trials showed no core at the end of the run. The core had dissipated into the skin during the run and the % core values were not significant enough for MoldFlow to detect (see Figure 13). Therefore, the entire bumper appears blue, which indicates 0% core throughout.

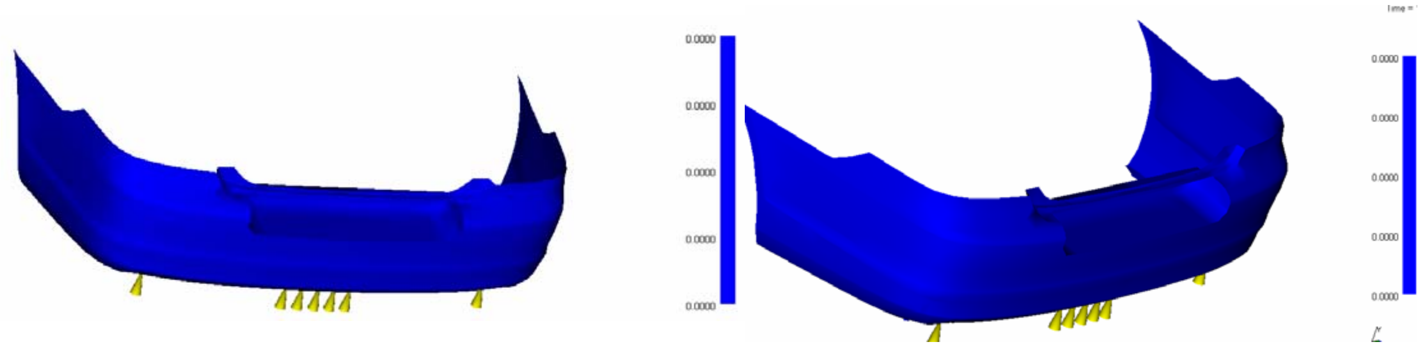

Figure 13: 15_260_220_5% and 25_220_260_5%, respectively;

Next, another 10% trial was run to determine the variations from injecting from the top. Surprisingly, one of the 10% trials, 25_220_260_10%, showed core surfacing on the back edges similar to the 20% and 30% core trials. This is shown in Figure 14 below.

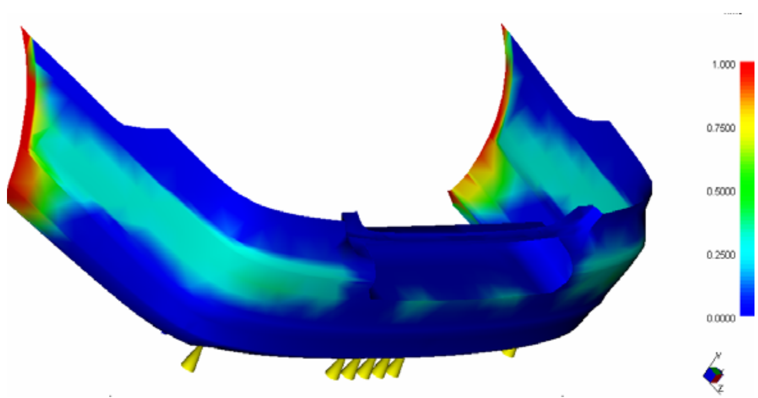

Figure 14: 25_220_260_10%; core surfacing on back edges

However, not all 10% core trials behaved this way when injected from the bottom. Trial 15_260_220_10% produced desirable results; there was no core surfacing and the core accumulated nicely in three distinct areas. This trial is shown in Figure 15. This proves that at 10% core, the process settings are critical in determining whether core surfacing will occur. Notice that in Figure 14, the core melt temperature was higher than the skin melt temperature and in Figure 10, the opposite is true.

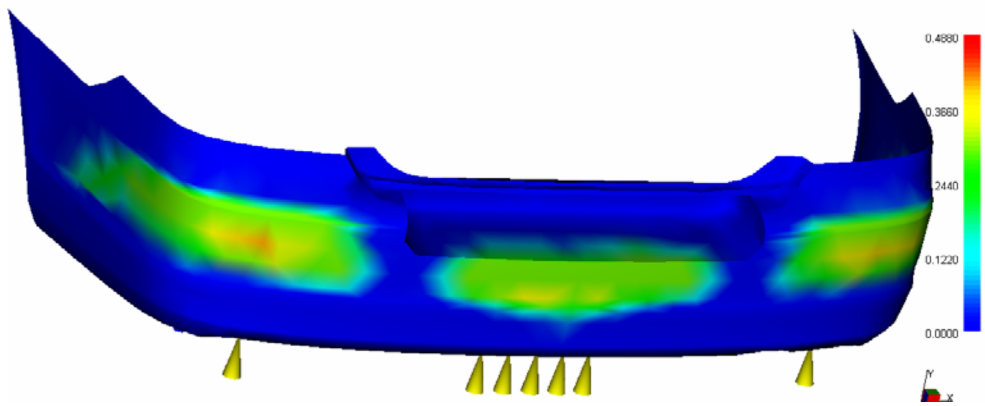

Figure 15: 15_260_220_10%; no core surfacing, distinct pockets of core material

The last step was to run 15% core trials. Core surfacing was evident again on the back edges of the bumper in trial 15_260_220_15%, seen in Figure 16.

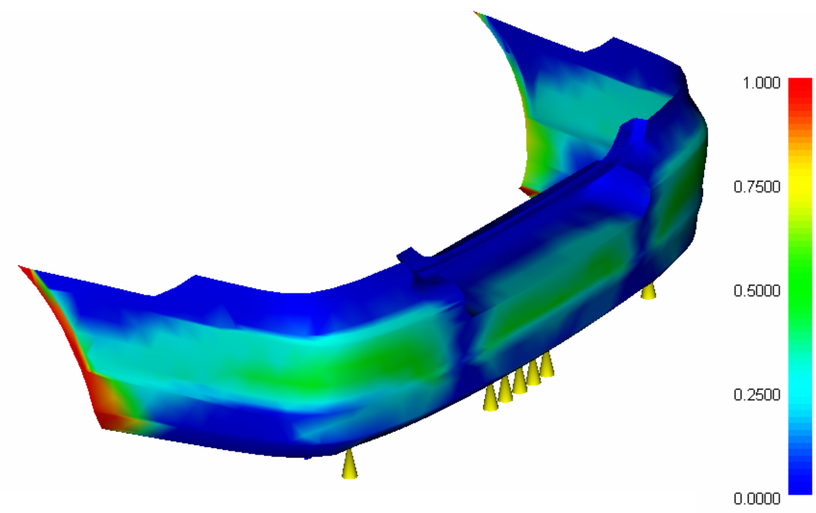

Figure 16: 15_260_220_15%, core surfacing shown on back edges

Another 15% trial (Figure 17) that was injected at the top did not show core surfacing but had thick pockets of core in three distinct areas. The core distribution reached 50% potentially making those parts of the bumper weaker. This may not be preferable if these areas are considered high-impact.

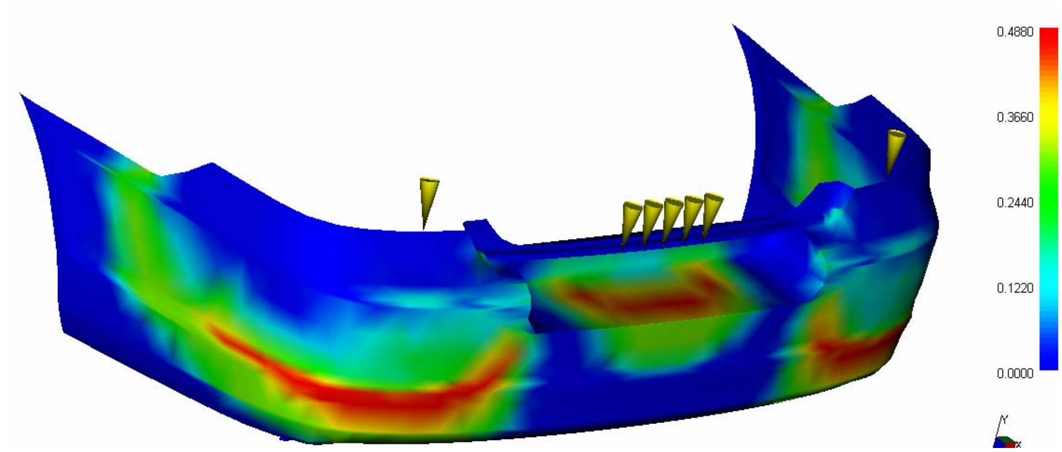

Figure 17: 25_220_260_15%; no core surfacing; thick pockets of core

In conclusion, the maximum amount of core material Honda should use for co-injection molding of their bumpers is 10%. From the preliminary runs, the best results occur when the skin melt temperature is greater than the core melt temperature. If the opposite is true, the core seems to move too easily through the skin and results in core surfacing on the back edges of the bumper.

Chapter VII. Future Work

Ohio State's Center for Advanced Polymers and Composite Engineering (CAPCE) has recently purchased a Battenfield co-injection molding machine that has arrived in the ISE manufacturing lab. A mold will be designed for this machine and it will be used to mold the optimum results from the statistical analysis and preliminary bumper runs. The samples will then undergo multiple tests of their physical properties to determine the most efficient variable settings according to Honda's specifications. Tests will include tensile strength (TS), flexural strength (FS), and impact resistance. This will take place on the Instron table-mounted materials testing system located in the ISE Labs as well as the CAPCE rheology lab. Fatigue testing will also be tested, as it is very important due to the internal interface in the bumper.

Along with the new equipment, future research will use the CAPCE rheology laboratory to measure the viscosity versus shear rate at several temperatures. Surface quality (Ra) will be evaluated in our labs using a profilometer, as well as equipment available in the CAPCE labs to measure surface tension. Small, flat plate samples will be provided to Honda for paint evaluation. Another option of using nanoclays to eliminate the painting process will also be investigated.

REFERENCES

1. Osswald, T. A. *Polymer Processing Fundamentals*. Hanser Publishers, (1998).

2. Groover, Mikell P. *Fundamentals of Modern Manufacturing*. Second Edition. John Wiley and Sons. (1999).

3. Turng, L. S., *Special and Emerging Injection Molding Technology*. Journal of Injection Molding Technology. 5:3 (2001).

4. Selden, R., *Sandwich Injection Molding of Thermoplastics – A Literature Survey*. Journal of Injection Molding Technology. 1:4 (1997).

5. Castillo, C., Honors Thesis (2006)

6. Nguyen, K.T., Turcott, E., Derdouri, A., Ait Messaoud, D., Sanschagrin, B., Salamon, B.A., Koppi, K.A., *Polymer Melt Flow Behavior in the Coinjection Holding Process.* ANTEC Proceedings (2000)

7. Watanabe, D., Hamada, H.M., Tomari, K., *Flow Behavior of Core Material in Sandwich Injection Molding with Sequential and Simultaneous Injection Molding.* ANTEC Proceedings (2002)

8. Turng, L.S., *Special and Emerging Injection Molding Technology.* Journal of Injection Molding Technology. 5:3 (2001)

9. Beasley, J.E., *Data Envelopment Analysis.* OR-Notes. Retrieved on March 31, 2007 from http://people.brunel.ac.uk/~mastjjb/jeb/or/dea.html

APPENDIX 1: DATA POINTS

Data Points for Dogbone Trials

						% core		
T mold C	A T melt C	B T melt C	% Core	Point 1	Point 2	Point 3	Point 4	Point 5
15	220	220	10	0.1415	0.1855	0.1955	0.3025	0
15	220	220	20	0.1515	0.3473	0.1855	0.488	0
15	220	220	30	0.1515	0.6248	0.488	0.488	0
15	220	240	10	0	0.1855	0.1995	0.3025	0
15	220	240	20	0.1515	0.1855	0.1855	0.488	0
15	220	240	30	0.1515	0.6412	0.488	0.488	0
15	220	260	10	0.0232	0.1855	0.2902	0.3025	0
15	220	260	20	0.1426	0.1855	0.1855	0.488	0
15	220	260	30	0.1515	0.6257	0.488	0.488	0
15	240	220	10	0.0807	0	0.1855	0.2122	0
15	240	220	20	0.1422	0.3381	0.1855	0.4544	0
15	240	220	30	0.1515	0.5545	0.488	0.488	0
15	240	240	10	0.1239	0.1855	0.1855	0.3025	0
15	240	240	20	0.1515	0.3087	0.1855	0.488	0
15	240	240	30	0.1515	0.5545	0.488	0.488	0
15	240	260	10	0.088	0.1855	0.1082	0.3025	0
15	240	260	20	0.1515	0.3284	0.1855	0.488	0
15	240	260	30	0.1515	0.5545	0.488	0.488	0
15	260	220	10	0.0841	0	0.1855	0.0661	0
15	260	220	20	0.1515	0.1855	0.385	0.488	0
15	260	220	30	0.1515	0.355	0.6137	0.488	0
15	260	240	10	0.02	0.1855	0.1957	0.3025	0
15	260	240	20	0.1515	0.355	0.1855	0.488	0
15	260	240	30	0.1515	0.4324	0.488	0.488	0
15	260	260	10	0.1388	0.1672	0.1855	0.3025	0
15	260	260	20	0.1515	0.1886	0.1855	0.488	0
15	260	260	30	0.1515	0.5545	0.488	0.488	0
20	220	220	10	0.1538	0.1855	0.1855	0.3025	0
20	220	220	20	0.1515	0.3517	0.1855	0.488	0
20	220	220	30	0.1515	0.5947	0.488	0.488	0
20	220	240	10	0.0427	0.1855	0.2244	0.3025	0
20	220	240	20	0.1621	0.2612	0.1943	0.488	0
20	220	240	30	0.1515	0.6351	0.488	0.488	0
20	220	260	10	0.0091	0.1855	0.3025	0.3025	0
20	220	260	20	0.0949	0.1855	0.184	0.488	0
20	220	260	30	0.1515	0.6575	0.488	0.488	0

						% core		
T mold C	A T melt C	B T melt C	% Core	Point 1	Point 2	Point 3	Point 4	Point 5
20	240	220	10	0.1017	0	0.1855	.29.4	0
20	240	220	20	0.1515	0.355	0.1855	0.488	0
20	240	220	30	0.1515	0.5512	0.488	0.488	0
20	240	240	10	0.0775	0.1855	0.1855	0.3025	0
20	240	240	20	0.1515	0.2943	0.1855	0.488	0
20	240	240	30	0.1515	0.5545	0.488	0.488	0
20	240	260	10	0.109	0.1855	0.1305	0.3025	0
20	240	260	20	0.1317	0.281	0.1855	0.488	0
20	240	260	30	0.1515	0.5545	0.488	0.488	0
20	260	220	10	0.1297	0	0.1855	0.1825	0
20	260	220	20	0.1524	0.2794	0.1855	0.3876	0
20	260	220	30	0.1515	0.355	0.5312	0.488	0
20	260	240	10	0.1262	0	0.1855	0.1995	0
20	260	240	20	0.1515	0.355	0.1855	0.488	0
20	260	240	30	0.1515	0.4055	0.488	0.488	0
20	260	260	10	0.1335	0.0591	0.1855	0.3097	0
20	260	260	20	0.1515	0.2349	0.1855	0.488	0
20	260	260	30	0.1515	0.4583	0.488	0.488	0
25	220	220	10	0.162	0.1855	0.1855	0.3205	0
25	220	220	20	0.1549	0.3456	0.1855	0.488	0
25	220	220	30	0.1515	0.6332	0.488	0.488	0
25	220	240	10	0.0915	0.1855	0.285	0.3205	0
25	220	240	20	0.1515	0.2372	0.1855	0.488	0
25	220	240	30	0.1515	0.6575	0.488	0.488	0
25	220	260	10	0	0.1855	0.3025	0.3205	0
25	220	260	20	0.1515	0.1869	0.2116	0.488	0
25	220	260	30	0.1515	0.6575	0.488	0.488	0
25	240	220	10	0.1515	0	0.1855	0.2685	0
25	240	220	20	0.1515	0.3545	0.1855	0.488	0
25	240	220	30	0.1515	0.5545	0.488	0.488	0
25	240	240	10	0.1212	0.1855	0.1855	0.3025	0
25	240	240	20	0.1515	0.355	0.1855	0.488	0
25	240	240	30	0.1515	0.5545	0.488	0.488	0
25	240	260	10	0.1004	0.1855	0.1995	0.3205	0
25	240	260	20	0.1515	0.3456	0.1855	0.488	0
25	240	260	30	0.1515	0.5785	0.488	0.488	0
25	260	220	10	0.0614	0	0.1855	0.1995	0
25	260	220	20	0.1515	0.2005	0.1855	0.385	0
25	260	220	30	0.1515	0.355	0.6588	0.488	0
25	260	240	10	0.129	0	0.1855	0.1955	0
25	260	240	20	0.1515	0.2801	0.1855	0.4505	0
25	260	240	30	0.1515	0.3426	0.488	0.488	0
25	260	260	10	0.1467	0.115	0.1855	0.3025	0
25	260	260	20	0.1515	0.2552	0.1855	0.488	0
25	260	260	30	0.1515	0.5545	0.488	0.488	0

APPENDIX 2: PERFORMANCE MEASURE VALUES

T mold C	A T melt C	B T melt C	% Core	(MPa) Max Pressure	(mm) Dist of max core from center	% core Max - Min in center	% core Difference btwn Pt1 and Pt5
15	220	220	10	8.629	4.11	0.117	0.1415
15	220	220	20	8.04	11.82	0.3025	0.1515
15	220	220	30	8.076	9.75	0.1368	0.1515
15	220	240	10	7.918	2.68	0.117	0
15	220	240	20	7.806	8.61	0.3025	0.1515
15	220	240	30	7.691	12.62	0.1532	0.1515
15	220	260	10	7.772	12.52	0.117	0.0232
15	220	260	20	7.327	9.09	0.3025	0.1426
15	220	260	30	7.226	14.91	0.1377	0.1515
15	240	220	10	7.633	18.07	0.2122	0.0807
15	240	220	20	7.91	16.16	0.2689	0.1422
15	240	220	30	8.203	2.68	0.0665	0.1515
15	240	240	10	7.312	14.43	0.117	0.1239
15	240	240	20	7.468	14.63	0.3025	0.1515
15	240	240	30	7.574	6.12	0.0665	0.1515
15	240	260	10	7.194	6.98	0.1943	0.088
15	240	260	20	7.18	12.52	0.3025	0.1515
15	240	260	30	7.16	8.7	0.0665	0.1515
15	260	220	10	6.737	21.7	0.1855	0.0841
15	260	220	20	7.105	6.88	0.3025	0.1515
15	260	220	30	7.5	0	0.2587	0.1515
15	260	240	10	7.814	19.88	0.117	0.02
15	260	240	20	6.795	14.63	0.3025	0.1515
15	260	240	30	7.022	3.45	0.0556	0.1515
15	260	260	10	6.347	16.83	0.1353	0.1388
15	260	260	20	6.458	15.49	0.3025	0.1515
15	260	260	30	6.852	7.45	0.0665	0.1515
20	220	220	10	8	8.89	0.117	0.1538
20	220	220	20	7.96	11.47	0.3025	0.1515
20	220	220	30	7.996	8.7	0.1067	0.1515
20	220	240	10	7.841	2.11	0.117	0.0427
20	220	240	20	7.729	8.13	0.2937	0.1621
20	220	240	30	7.618	12.62	0.1471	0.1515
20	220	260	10	7.696	6.5	0.117	0.0091
20	220	260	20	7.256	8.32	0.304	0.0949
20	220	260	30	7.201	14.15	0.1695	0.1515

T mold C	A T melt C	B T melt C	% Core	(MPa) Max Pressure	(mm) Dist of max core from center	% core Max - Min in center	% core Difference between Pt1 and Pt5
20	240	220	10	7.336	17.3	0.1855	0.1017
20	240	220	20	7.547	13.57	0.3025	0.1515
20	240	220	30	7.807	3.92	0.0632	0.1515
20	240	240	10	6.995	12.24	0.117	0.0775
20	240	240	20	7.102	13.19	0.3025	0.1515
20	240	240	30	7.168	6.6	0.0665	0.1515
20	240	260	10	6.877	6.21	0.172	0.109
20	240	260	20	6.848	10.42	0.3025	0.1317
20	240	260	30	6.782	9.56	0.0665	0.1515
20	260	220	10	6.665	20.84	0.1855	0.1297
20	260	220	20	7.032	17.21	0.2021	0.1524
20	260	220	30	7.437	0	0.1762	0.1515
20	260	240	10	6.553	18.83	0.1995	0.1262
20	260	240	20	6.744	13.48	0.3025	0.1515
20	260	240	30	6.964	3.25	0.0825	0.1515
20	260	260	10	6.425	15.39	0.2506	0.1335
20	260	260	20	6.535	15.3	0.3025	0.1515
20	260	260	30	6.491	5.35	0.0297	0.1515
25	220	220	10	7.803	9.18	0.135	0.162
25	220	220	20	7.88	11.66	0.3025	0.1549
25	220	220	30	8.018	8.51	0.1452	0.1515
25	220	240	10	7.761	5.46	0.135	0.0915
25	220	240	20	7.653	7.75	0.3025	0.1515
25	220	240	30	7.541	11.57	0.1695	0.1515
25	220	260	10	7.42	6.69	0.135	0
25	220	260	20	7.187	7.08	0.3011	0.1515
25	220	260	30	7.131	13.66	0.1695	0.1515
25	240	220	10	7.269	17.59	0.2685	0.1515
25	240	220	20	7.481	14.73	0.3025	0.1515
25	240	220	30	7.717	3.55	0.0665	0.1515
25	240	240	10	6.933	12.04	0.117	0.1212
25	240	240	20	7.038	12.04	0.3025	0.1515
25	240	240	30	7.101	6.88	0.0665	0.1515
25	240	260	10	6.819	4.87	0.135	0.1004
25	240	260	20	6.76	10.23	0.3025	0.1515
25	240	260	30	6.724	9	0.0905	0.1515
25	260	220	10	6.613	20.94	0.1995	0.0614
25	260	220	20	6.98	18.64	0.1995	0.1515
25	260	220	30	7.375	0	0.3038	0.1515
25	260	240	10	6.506	19.02	0.1955	0.129
25	260	240	20	6.696	15.68	0.265	0.1515
25	260	240	30	6.911	2.4	0.1454	0.1515
25	260	260	10	6.377	14.34	0.1875	0.1467
25	260	260	20	6.483	13.96	0.3025	0.1515
25	260	260	30	6.441	5.45	0.0665	0.1515

APPENDIX 3: MINITAB RESULTS

Response Surface Regression: Max Pressure versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Max Pressure

Term	Coef	SE Coef	T	P
Constant	22.8616	9.43041	2.424	0.018
T mold C	-0.1945	0.11694	-1.663	0.101
A T melt C	-0.0591	0.05172	-1.142	0.258
B T melt C	-0.0089	0.05172	-0.172	0.864
% Core	-0.0654	0.05231	-1.250	0.216
T mold C*T mold C	0.0031	0.00161	1.910	0.061
A T melt C*A T melt C	0.0000	0.00010	0.073	0.942
B T melt C*B T melt C	-0.0000	0.00010	-0.363	0.718
% Core*% Core	0.0006	0.00040	1.365	0.177
T mold C*A T melt C	-0.0000	0.00029	-0.153	0.879
T mold C*B T melt C	0.0001	0.00029	0.510	0.612
T mold C*% Core	0.0008	0.00057	1.471	0.146
A T melt C*B T melt C	0.0001	0.00007	1.122	0.266
A T melt C*% Core	0.0007	0.00014	5.162	0.000
B T melt C*% Core	-0.0006	0.00014	-4.251	0.000

S = 0.1710   R-Sq = 91.1%   R-Sq(adj) = 89.2%

Analysis of Variance for Max Pressure

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	19.7259	19.72591	1.408994	48.16	0.000
Linear	4	18.1438	0.15323	0.038307	1.31	0.276
Square	4	0.1652	0.16520	0.041300	1.41	0.240
Interaction	6	1.4169	1.41688	0.236147	8.07	0.000
Residual Error	66	1.9308	1.93084	0.029255		
Total	80	21.6568				

Unusual Observations for Max Pressure

Obs	StdOrder	Max Pressure	Fit	SE Fit	Residual	St Resid
1	1	8.629	8.293	0.090	0.336	2.31 R
19	19	6.737	7.043	0.090	-0.306	-2.11 R
22	22	7.814	6.867	0.075	0.947	6.17 R
25	25	6.347	6.662	0.090	-0.315	-2.17 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Dist max cor versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Dist max core from center

Term	Coef	SE Coef	T	P
Constant	-50.7519	134.024	-0.379	0.706
T mold C	1.2956	1.662	0.780	0.438

A T melt C	0.4954	0.735	0.674	0.503
B T melt C	-0.4216	0.735	-0.574	0.568
% Core	3.7126	0.743	4.994	0.000
T mold C*T mold C	0.0063	0.023	0.276	0.784
A T melt C*A T melt C	0.0003	0.001	0.210	0.834
B T melt C*B T melt C	0.0008	0.001	0.587	0.559
% Core*% Core	-0.0257	0.006	-4.489	0.000
T mold C*A T melt C	0.0024	0.004	0.594	0.554
T mold C*B T melt C	-0.0091	0.004	-2.252	0.028
T mold C*% Core	0.0013	0.008	0.165	0.869
A T melt C*B T melt C	-0.0004	0.001	-0.376	0.708
A T melt C*% Core	-0.0262	0.002	-12.943	0.000
B T melt C*% Core	0.0138	0.002	6.816	0.000

S = 2.431   R-Sq = 83.2%   R-Sq(adj) = 79.6%

Analysis of Variance for Dist max core from center

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	1926.67	1926.67	137.620	23.29	0.000
Linear	4	507.46	155.55	38.887	6.58	0.000
Square	4	121.82	121.82	30.455	5.15	0.001
Interaction	6	1297.39	1297.39	216.231	36.59	0.000
Residual Error	66	389.99	389.99	5.909		
Total	80	2316.66				

Unusual Observations for Dist max core from center

Obs	StdOrder	Dist max core from center	Fit	SE Fit	Residual	St Resid	
1	1	4.110	8.450	1.281	-4.340	-2.10	R
7	7	12.520	4.430	1.281	8.090	3.92	R
20	20	6.880	13.461	1.072	-6.581	-3.02	R
61	61	6.690	1.628	1.281	5.062	2.45	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Max-min in c versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Max-min in center

Term	Coef	SE Coef	T	P
Constant	1.48784	2.61553	0.569	0.571
T mold C	-0.01110	0.03243	-0.342	0.733
A T melt C	-0.00878	0.01434	-0.612	0.543
B T melt C	-0.00790	0.01434	-0.551	0.584
% Core	0.09277	0.01451	6.395	0.000
T mold C*T mold C	0.00026	0.00045	0.586	0.560
A T melt C*A T melt C	0.00004	0.00003	1.367	0.176
B T melt C*B T melt C	0.00003	0.00003	1.196	0.236
% Core*% Core	-0.00155	0.00011	-13.826	0.000
T mold C*A T melt C	0.00001	0.00008	0.105	0.916
T mold C*B T melt C	-0.00000	0.00008	-0.025	0.980
T mold C*% Core	0.00001	0.00016	0.069	0.945
A T melt C*B T melt C	-0.00003	0.00002	-1.608	0.113

A T melt C*% Core	-0.00010	0.00004	-2.457	0.017
B T melt C*% Core	-0.00004	0.00004	-1.049	0.298

S = 0.04744   R-Sq = 76.7%   R-Sq(adj) = 71.8%

Analysis of Variance for Max-min in center

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	0.489399	0.489399	0.034957	15.53	0.000
Linear	4	0.029120	0.095040	0.023760	10.56	0.000
Square	4	0.438362	0.438362	0.109591	48.70	0.000
Interaction	6	0.021917	0.021917	0.003653	1.62	0.155
Residual Error	66	0.148527	0.148527	0.002250		
Total	80	0.637926				

Unusual Observations for Max-min in center

Obs	StdOrder	Max-min in center	Fit	SE Fit	Residual	St Resid	
21	21	0.259	0.133	0.025	0.126	3.13	R
47	47	0.202	0.320	0.018	-0.118	-2.68	R
64	64	0.269	0.159	0.021	0.109	2.57	R
74	74	0.200	0.333	0.021	-0.134	-3.14	R
75	75	0.304	0.147	0.025	0.157	3.89	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Diff btwn Pt versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Diff btwn Pt1 and Pt5

Term	Coef	SE Coef	T	P
Constant	2.15284	1.37621	1.564	0.123
T mold C	0.00909	0.01706	0.533	0.596
A T melt C	-0.00242	0.00755	-0.321	0.749
B T melt C	-0.01677	0.00755	-2.222	0.030
% Core	0.01697	0.00763	2.223	0.030
T mold C*T mold C	0.00001	0.00024	0.039	0.969
A T melt C*A T melt C	-0.00001	0.00001	-0.966	0.337
B T melt C*B T melt C	0.00001	0.00001	0.754	0.453
% Core*% Core	-0.00026	0.00006	-4.356	0.000
T mold C*A T melt C	-0.00000	0.00004	-0.046	0.963
T mold C*B T melt C	-0.00002	0.00004	-0.503	0.617
T mold C*% Core	-0.00015	0.00008	-1.759	0.083
A T melt C*B T melt C	0.00004	0.00001	4.252	0.000
A T melt C*% Core	-0.00005	0.00002	-2.308	0.024
B T melt C*% Core	0.00004	0.00002	2.121	0.038

S = 0.02496   R-Sq = 67.1%   R-Sq(adj) = 60.1%

Analysis of Variance for Diff btwn Pt1 and Pt5

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	0.083719	0.083719	0.005980	9.60	0.000
Linear	4	0.051485	0.006658	0.001664	2.67	0.040
Square	4	0.012761	0.012761	0.003190	5.12	0.001

Interaction	6	0.019473	0.019473	0.003246	5.21	0.000
Residual Error	66	0.041120	0.041120	0.000623		
Total	80	0.124839				

Unusual Observations for Diff btwn Pt1 and Pt5

Obs	StdOrder	Diff btwn Pt1 and Pt5	Fit	SE Fit	Residual	St Resid	
1	1	0.142	0.096	0.013	0.045	2.14	R
4	4	0.000	0.060	0.011	-0.060	-2.67	R
22	22	0.020	0.094	0.011	-0.074	-3.31	R
61	61	0.000	0.054	0.013	-0.054	-2.54	R
73	73	0.061	0.124	0.013	-0.063	-2.95	R

R denotes an observation with a large standardized residual.

ITERATIONS:

Response Surface Regression: Max Pressure versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Max Pressure – 1st iteration

Term	Coef	SE Coef	T	P
Constant	19.4471	1.21770	15.970	0.000
T mold C	-0.1701	0.06411	-2.652	0.010
A T melt C	-0.0372	0.00301	-12.386	0.000
B T melt C	-0.0043	0.00301	-1.445	0.153
% Core	-0.0654	0.05107	-1.280	0.205
T mold C*T mold C	0.0031	0.00157	1.956	0.054
% Core*% Core	0.0006	0.00039	1.398	0.166
T mold C*% Core	0.0008	0.00056	1.507	0.136
A T melt C*% Core	0.0007	0.00014	5.288	0.000
B T melt C*% Core	-0.0006	0.00014	-4.354	0.000

S = 0.1670   R-Sq = 90.9%   R-Sq(adj) = 89.7%

Analysis of Variance for Max Pressure

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	19.6768	19.67682	2.18631	78.40	0.000
Linear	4	18.1438	9.97255	2.49314	89.40	0.000
Square	2	0.1612	0.16119	0.08060	2.89	0.062
Interaction	3	1.3718	1.37180	0.45727	16.40	0.000
Residual Error	71	1.9799	1.97993	0.02789		
Total	80	21.6568				

Unusual Observations for Max Pressure

Obs	StdOrder	Max Pressure	Fit	SE Fit	Residual	St Resid	
1	1	8.629	8.255	0.071	0.374	2.48	R
19	19	6.737	7.060	0.071	-0.323	-2.14	R
22	22	7.814	6.852	0.062	0.962	6.20	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Max Pressure versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Max Pressure after 2 iterations –

Term	Coef	SE Coef	T	P
Constant	18.9281	1.20797	15.669	0.000
T mold C	-0.1533	0.06410	-2.391	0.019
A T melt C	-0.0372	0.00305	-12.201	0.000
B T melt C	-0.0043	0.00305	-1.423	0.159
% Core	-0.0266	0.04800	-0.554	0.582
T mold C*T mold C	0.0031	0.00160	1.927	0.058
A T melt C*% Core	0.0007	0.00014	5.209	0.000
B T melt C*% Core	-0.0006	0.00014	-4.290	0.000

S = 0.1695   R-Sq = 90.3%   R-Sq(adj) = 89.4%

Analysis of Variance for Max Pressure

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	19.5590	19.5590	2.79414	97.23	0.000
Linear	4	18.1438	18.3514	4.58786	159.65	0.000
Square	1	0.1067	0.1067	0.10667	3.71	0.058
Interaction	2	1.3085	1.3085	0.65423	22.77	0.000
Residual Error	73	2.0978	2.0978	0.02874		
Total	80	21.6568				

Unusual Observations for Max Pressure

Obs	StdOrder	Max Pressure	Fit	SE Fit	Residual	St Resid	
1	1	8.629	8.195	0.065	0.434	2.78	R
22	22	7.814	6.792	0.054	1.022	6.36	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Max Pressure versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Max Pressure after 3 iterations – FINAL

Term	Coef	SE Coef	T	P
Constant	17.7477	1.05998	16.743	0.000
T mold C	-0.0301	0.00470	-6.411	0.000
A T melt C	-0.0372	0.00311	-11.983	0.000
B T melt C	-0.0043	0.00311	-1.398	0.166
% Core	-0.0266	0.04887	-0.544	0.588
A T melt C*% Core	0.0007	0.00014	5.116	0.000
B T melt C*% Core	-0.0006	0.00014	-4.213	0.000

S = 0.1726   R-Sq = 89.8%   R-Sq(adj) = 89.0%

Analysis of Variance for Max Pressure

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	6	19.4523	19.4523	3.24205	108.83	0.000
Linear	4	18.1438	19.4114	4.85285	162.90	0.000
Interaction	2	1.3085	1.3085	0.65423	21.96	0.000
Residual Error	74	2.2045	2.2045	0.02979		
Total	80	21.6568				

Unusual Observations for Max Pressure

Obs	StdOrder	Max Pressure	Fit	SE Fit	Residual	St Resid
1	1	8.629	8.169	0.065	0.460	2.88 R
22	22	7.814	6.766	0.053	1.048	6.38 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Dist max cor versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Dist max core from center after 1 iteration - FINAL

Term	Coef	SE Coef	T	P
Constant	-108.779	23.7186	-4.586	0.000
T mold C	2.153	0.9400	2.290	0.025
A T melt C	0.596	0.0422	14.130	0.000
B T melt C	-0.109	0.0888	-1.231	0.222
% Core	3.739	0.6998	5.344	0.000
% Core*% Core	-0.026	0.0055	-4.654	0.000
T mold C*B T melt C	-0.009	0.0039	-2.334	0.022
A T melt C*% Core	-0.026	0.0020	-13.418	0.000
B T melt C*% Core	0.014	0.0020	7.066	0.000

S = 2.345   R-Sq = 82.9%   R-Sq(adj) = 81.0%

Analysis of Variance for Dist max core from center

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	8	1920.85	1920.85	240.106	43.68	0.000
Linear	4	507.46	1391.22	347.806	63.27	0.000
Square	1	119.08	119.08	119.077	21.66	0.000
Interaction	3	1294.30	1294.30	431.435	78.48	0.000
Residual Error	72	395.82	395.82	5.497		
Total	80	2316.66				

Unusual Observations for Dist max core from center

Obs	StdOrder	Dist max core from center	Fit	SE Fit	Residual	St Resid
7	7	12.520	3.765	0.983	8.755	4.11 R
20	20	6.880	13.345	0.813	-6.465	-2.94 R
61	61	6.690	1.578	0.983	5.112	2.40 R

R denotes an observation with a large standardized residual.

Response Surface Regression: Max-min in c versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Max-min in center after 1 iteration

Term	Coef	SE Coef	T	P
Constant	-0.364758	1.93545	-0.188	0.851
T mold C	0.001121	0.00126	0.888	0.377
A T melt C	-0.008611	0.01395	-0.617	0.539
B T melt C	0.007273	0.00465	1.564	0.122
% Core	0.083028	0.01028	8.077	0.000
A T melt C*A T melt C	0.000038	0.00003	1.397	0.167
% Core*% Core	-0.001546	0.00011	-14.134	0.000
A T melt C*B T melt C	-0.000032	0.00002	-1.644	0.104
A T melt C*% Core	-0.000097	0.00004	-2.511	0.014

S = 0.04640   R-Sq = 75.7%   R-Sq(adj) = 73.0%

Analysis of Variance for Max-min in center

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	8	0.482894	0.482894	0.060362	28.03	0.000
Linear	4	0.029120	0.153200	0.038300	17.79	0.000
Square	2	0.434373	0.434373	0.217186	100.87	0.000
Interaction	2	0.019402	0.019402	0.009701	4.51	0.014
Residual Error	72	0.155032	0.155032	0.002153		
Total	80	0.637926				

Unusual Observations for Max-min in center

Obs	StdOrder	Max-min in center	Fit	SE Fit	Residual	St Resid	
21	21	0.259	0.119	0.018	0.139	3.27	R
47	47	0.202	0.320	0.015	-0.118	-2.69	R
64	64	0.269	0.161	0.015	0.107	2.44	R
74	74	0.200	0.326	0.017	-0.126	-2.91	R
75	75	0.304	0.130	0.018	0.173	4.06	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Max-min in c versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Max-min in center after 2 iterations - FINAL

Term	Coef	SE Coef	T	P
Constant	-0.723904	0.223192	-3.243	0.002
T mold C	0.001121	0.001285	0.872	0.386
A T melt C	0.002096	0.000850	2.466	0.016
B T melt C	-0.000357	0.000321	-1.111	0.270
% Core	0.083028	0.010462	7.936	0.000
% Core*% Core	-0.001546	0.000111	-13.887	0.000
A T melt C*% Core	-0.000097	0.000039	-2.467	0.016

S = 0.04723   R-Sq = 74.1%   R-Sq(adj) = 72.0%

Analysis of Variance for Max-min in center

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	6	0.472869	0.472869	0.078811	35.33	0.000
Linear	4	0.029120	0.273488	0.068372	30.65	0.000
Square	1	0.430169	0.430169	0.430169	192.86	0.000
Interaction	1	0.013580	0.013580	0.013580	6.09	0.016
Residual Error	74	0.165057	0.165057	0.002231		
Total	80	0.637926				

Unusual Observations for Max-min in center

Obs	StdOrder	Max-min in center	Fit	SE Fit	Residual	St Resid	
21	21	0.259	0.101	0.016	0.157	3.55	R
47	47	0.202	0.302	0.013	-0.100	-2.20	R
64	64	0.269	0.171	0.013	0.097	2.14	R
74	74	0.200	0.308	0.014	-0.108	-2.41	R
75	75	0.304	0.113	0.016	0.191	4.31	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Diff btwn Pt versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Diff btwn Pt1 and Pt5 after 1 iteration

Term	Coef	SE Coef	T	P
Constant	2.43779	0.605258	4.028	0.000
T mold C	0.00398	0.001756	2.269	0.026
A T melt C	-0.00928	0.002478	-3.747	0.000
B T melt C	-0.01186	0.002478	-4.789	0.000
% Core	0.01697	0.007457	2.275	0.026
% Core*% Core	-0.00026	0.000057	-4.459	0.000
T mold C*% Core	-0.00015	0.000081	-1.801	0.076
A T melt C*B T melt C	0.00004	0.000010	4.353	0.000
A T melt C*% Core	-0.00005	0.000020	-2.362	0.021
B T melt C*% Core	0.00004	0.000020	2.171	0.033

S = 0.02438   R-Sq = 66.2%   R-Sq(adj) = 61.9%

Analysis of Variance for Diff btwn Pt1 and Pt5

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.082623	0.082623	0.009180	15.44	0.000
Linear	4	0.051485	0.027600	0.006900	11.60	0.000
Square	1	0.011824	0.011824	0.011824	19.89	0.000
Interaction	4	0.019314	0.019314	0.004829	8.12	0.000
Residual Error	71	0.042216	0.042216	0.000595		
Total	80	0.124839				

Unusual Observations for Diff btwn Pt1 and Pt5

Diff

Obs	StdOrder	btwn Pt1 and Pt5	Fit	SE Fit	Residual	St Resid	
4	4	0.000	0.065	0.009	-0.065	-2.85	R
22	22	0.020	0.099	0.009	-0.079	-3.46	R
61	61	0.000	0.056	0.011	-0.056	-2.58	R
73	73	0.061	0.122	0.011	-0.061	-2.80	R

R denotes an observation with a large standardized residual.

Response Surface Regression: Diff btwn Pt versus T mold C, A T melt C, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Diff btwn Pt1 and Pt5 after 2nd iteration - FINAL

Term	Coef	SE Coef	T	P
Constant	2.49635	0.613729	4.068	0.000
T mold C	0.00106	0.000674	1.567	0.122
A T melt C	-0.00928	0.002516	-3.690	0.000
B T melt C	-0.01186	0.002516	-4.716	0.000
% Core	0.01404	0.007390	1.900	0.061
% Core*% Core	-0.00026	0.000058	-4.391	0.000
A T melt C*B T melt C	0.00004	0.000010	4.286	0.000
A T melt C*% Core	-0.00005	0.000021	-2.326	0.023
B T melt C*% Core	0.00004	0.000021	2.138	0.036

S = 0.02476   R-Sq = 64.6%   R-Sq(adj) = 60.7%

Analysis of Variance for Diff btwn Pt1 and Pt5

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	8	0.080694	0.080694	0.010087	16.45	0.000
Linear	4	0.051485	0.026260	0.006565	10.71	0.000
Square	1	0.011824	0.011824	0.011824	19.28	0.000
Interaction	3	0.017386	0.017386	0.005795	9.45	0.000
Residual Error	72	0.044145	0.044145	0.000613		
Total	80	0.124839				

Unusual Observations for Diff btwn Pt1 and Pt5

Obs	StdOrder	Diff btwn Pt1 and Pt5	Fit	SE Fit	Residual	St Resid	
4	4	0.000	0.072	0.008	-0.072	-3.07	R
22	22	0.020	0.106	0.008	-0.086	-3.67	R
55	55	0.162	0.117	0.010	0.045	2.02	R
61	61	0.000	0.049	0.010	-0.049	-2.17	R
73	73	0.061	0.115	0.010	-0.054	-2.39	R

R denotes an observation with a large standardized residual.